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A TECHNIQUE FOR DETERMINING PLANETARY ATMOSPHERE STRUCTURE FROM MEASURED ACCELERATIONS OF AN ENTRY VEHICLE

by Victor L. Peterson
Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1965

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A TECHNIQUE FOR DETERMINING PLANETARY ATMOSPHERE STRUCTURE FROM MEASURED ACCELERATIONS OF AN ENTRY VEHICLE

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SUMMARY

A detailed procedure has been developed for obtaining the density and pressure structure of a planetary atmosphere from measurements of accelerations experienced by a vehicle making an uncontrolled entry into the atmosphere. It has been shown that considerable simplification in the method is possible and a potentially large source of error is eliminated if the accelerometers are carried by a spherically shaped vehicle.

Sample calculations were made to illustrate how well extreme model atmospheres for Mars could be defined by this technique. Results of the calculations showed that accelerometers designed to measure over the entire range of expected accelerations with an accuracy of 0.1 percent of full-scale capability would not provide sufficiently precise data to define all of the atmospheres that could be encountered within the possible extremes. If, however, the time period over which large errors in measured accelerations are encountered is reduced by means of an independent method for defining the atmosphere during the portion of the flight when the speed is relatively low or the acceleration measurements are improved by resorting to a dual system in which one set of instruments measures over the entire range of expected accelerations and the other over a more limited range, then any of the model atmospheres within the extremes can be determined reasonably well over extensive ranges of altitude. It is concluded that the method is worthy of further consideration as a means for surveying the atmospheres of the planets.

INTRODUCTION

An objective of early programs to explore the planets will probably be to measure the properties of their surrounding atmospheres. Information of this nature is certainly needed since current estimates of the properties of planetary atmospheres, which are based on astronomical observations, are not adequate to permit the design of efficient advanced entry vehicles.

A number of methods for measuring the variations of density and pressure with altitude in an atmosphere have been devised. Descriptions of some of those which have been used to survey the Earth's atmosphere are reported in references 1 and 2. In one of the methods the ambient density is determined from measurements of the accelerations experienced by a body in free fall. A relationship between accelerations due to aerodynamic loads and local atmosphere density can be expressed in terms of the aerodynamic characteristics of the body. The aerodynamics of the body are given, of course, either by theory or by experiments. In the application of this technique to the problem of surveying the Earth's atmosphere, the trajectory of the body is obtained either by tracking the flight with instruments not aboard the vehicle or by reconstruction of the trajectory using the equations of motion and the measured accelerations. Thus, from the time history of ambient density given by the measured accelerations and the time history of altitude given by the trajectory data, a record of density variation with altitude can be constructed.

In reference 3 the suggestion was made to apply the general technique of deducing atmosphere structure from measurements of vehicle accelerations to the problem of surveying the atmospheres of planets other than Earth. It was shown in reference 3 that in addition to ambient density, the pressure, the product of gas constant and temperature, and the altitude all could be obtained from a time history of the accelerations experienced by a vehicle making a high-speed entry into a planetary atmosphere. It was observed, however, that if attitude control were not provided, then the effects of angle-of-attack oscillations on the measurements could be significant and, in fact, probably would require the additional measurement of a continuous record of vehicle attitude.

The purpose of the present study is to amplify and extend some of the ideas presented in reference 3. In particular, a detailed procedure for obtaining atmosphere structure from measurements made by on-board accelerometers is developed.[1] The equations are used to show how the selection of a particular body configuration simplifies the technique by completely eliminating the need for considering body attitude. Finally, some estimates are made of the inaccuracies in atmosphere definition due to errors in measuring accelerations.

NOTATION

a	resultant acceleration due to aerodynamic loads, $\sqrt{a_x^2 + a_y^2 + a_z^2}$
a_x,a_y,a_z	accelerations due to aerodynamic loads along the x, y, z body axes, respectively (eqs. (1))
A	reference area for aerodynamic coefficients

[1]Portions of the method presented herein have been derived previously in references 1 and 2 in which results of surveys of the Earth's atmosphere using bodies in low-speed free fall are reported. However, the method is redeveloped completely in the present study for clarity and completeness.

C_A axial-force coefficient, $\dfrac{\text{axial force}}{\frac{1}{2}\rho V^2 A}$

C_D drag-force coefficient, $\dfrac{\text{drag force}}{\frac{1}{2}\rho V^2 A}$

C_L lift-force coefficient, $\dfrac{\text{lift force}}{\frac{1}{2}\rho V^2 A}$

C_N normal-force coefficient, $\dfrac{\text{normal force}}{\frac{1}{2}\rho V^2 A}$

C_Y side-force coefficient, $\dfrac{\text{side force}}{\frac{1}{2}\rho V^2 A}$

g local acceleration of gravity

h altitude above planet surface

H_ρ local atmosphere scale height (eq. (6))

m vehicle mass

p ambient pressure in atmosphere

r distance from planet center to vehicle mass center

R gas constant for atmosphere gas mixture, $\dfrac{p}{\rho T}$

t time

T ambient temperature of atmosphere

V flight speed

x,y,z body axes with origin at vehicle mass center (fig. (1))

θ flight-path angle measured relative to local horizontal

ρ ambient density of atmosphere

σ angle of body incidence (fig. (1))

φ angle of body roll (fig. (1))

Subscripts

E quantity evaluated at entry

o quantity evaluated at planet surface

ANALYSIS

The trajectory of a body entering a planetary atmosphere is sensitive to the variation of atmosphere density with altitude. Normally, the density structure of an atmosphere is presumed known and the trajectory of a body is calculated using given conditions at entry. In reference 3 attention was focused on the possibility of reversing the situation in order to determine an unknown atmosphere structure from measurements of the accelerations experienced by a vehicle flying through the atmosphere in question. The concept was not examined in detail in reference 3, however.

The purpose of this analysis is to develop in more detail the technique for calculating atmosphere density, pressure, and scale height as functions of altitude from measurements made by accelerometers. In addition, it will be shown that the method can be significantly simplified and that a source of potentially large errors can be eliminated completely by the use of a particular vehicle configuration. Finally, results of calculations of the inaccuracies in the definitions of atmospheres due to errors in accelerometer measurements are presented.

Method for Obtaining Atmosphere Structure

First, equations will be presented relating the density, pressure, scale height, and altitude to the trajectory variables, speed, path angle, and time. Then, methods for determining the trajectory from acceleration measurements will be discussed. It will be seen that all of the quantities can be determined without specifying the chemical composition of the atmosphere and without assuming an adiabatic or isothermal atmosphere.

Consider a body at an arbitrary attitude relative to the velocity vector and assume that accelerometers located within the body at the center of mass are alined with a set of x, y, z body axes. The axes and angles are defined in figure 1. Let the accelerometers be designed to measure both positive and negative values. The instruments will react only to aerodynamic forces when the body enters an atmosphere so that the governing equations are

$$\left.\begin{aligned} a_x &= \frac{C_A A}{m}\left(\frac{1}{2}\rho V^2\right) \\ a_y &= \frac{C_Y A}{m}\left(\frac{1}{2}\rho V^2\right) \\ a_z &= \frac{C_N A}{m}\left(\frac{1}{2}\rho V^2\right) \end{aligned}\right\} \tag{1}$$

Any one of equations (1) can be solved for density ρ in terms of the speed, a force coefficient, some constants, and a measured acceleration. The largest accelerations will generally be in the direction of the axial force so that it is reasonable to solve for density from the first of equations (1). The result is

$$\rho = \left(\frac{m}{C_A A}\right)\frac{2}{V^2}a_x \tag{2}$$

The atmosphere pressure can be obtained directly by integrating the barometric equation

$$dp = -g\rho\ dh$$

to give

$$\int_{p_E}^{p} dp = -\int_{h_E}^{h} g\rho\ dh$$

The rate of change of altitude with time is given by

$$\frac{dh}{dt} = -V \sin\theta \tag{3}$$

Equation (3) can be used to write the pressure relation

$$p - p_E = \int_0^t g\rho\ V \sin\theta\ dt \tag{4}$$

The time is measured from the moment when the accelerometers first record usable readings. It is anticipated that the accelerometers selected for use will measure small values of acceleration relative to the maximum encountered along the trajectory. In this case, the portion of the planetary atmosphere above the altitude corresponding to zero time will be small relative to the total atmosphere. For these circumstances, the pressure at time zero can be neglected so that equation (4) can be written as follows:

$$p = \int_0^t g\rho\ V \sin\theta\ dt \tag{5}$$

The local density scale height is given by

$$H_\rho = \frac{RT}{g} \tag{6}$$

If it is assumed that the ambient atmosphere behaves as a thermally perfect gas, then the following relationship between thermodynamic variables is valid

$$RT = \frac{p}{\rho}$$

Substituting the above relation into equation (6) leads to an equation for density scale height in terms of pressure and density

$$H_\rho = \frac{1}{g}\frac{p}{\rho} \tag{7}$$

Finally, the altitude is obtained from the integration of equation (3). The result is

$$h = h_E - \int_0^t V \sin \theta \, dt \tag{8}$$

Equations (2), (5), (7), and (8) constitute the relations linking the atmosphere structure to the trajectory variables. It is noted that in addition to the explicit dependence on V, θ, and t there is an implicit dependence of density, pressure, scale height, and altitude on vehicle attitude through the axial force coefficient in equation (2). The problem now is to determine the time history of the speed V and path angle θ. The atmosphere structure will be defined when this is accomplished.

The equations governing the trajectory of a body entering a spherically symmetric nonrotating planetary atmosphere can be written as follows:

$$\left.\begin{aligned} \frac{1}{g}\frac{dV}{dt} + \frac{1}{g}\left(\frac{C_D A}{m}\right)\left(\frac{1}{2}\rho V^2\right) - \sin\theta = 0 \\ \frac{V}{g}\frac{d\theta}{dt} + \left(\frac{V^2}{gr} - 1\right)\cos\theta + \frac{1}{g}\left(\frac{C_L A}{m}\right)\left(\frac{1}{2}\rho V^2\right) = 0 \end{aligned}\right\} \tag{9}$$

The first of these equations expresses a balance of forces along the flight path and the second expresses a balance of forces in the direction normal to the flight path. Reference to equations (1) shows that the dynamic pressure $(1/2)\rho V^2$ can be written in terms of one of the accelerometer readings, say

$$\frac{1}{2}\rho V^2 = \left(\frac{m}{C_A A}\right) a_x$$

Substituting this relation for the dynamic pressure in equations (9) gives

$$\left.\begin{aligned} \frac{1}{g}\frac{dV}{dt} + \frac{C_D}{C_A}\left(\frac{a_x}{g}\right) - \sin\theta = 0 \\ \frac{V}{g}\frac{d\theta}{dt} + \left(\frac{V^2}{gr} - 1\right)\cos\theta + \frac{C_L}{C_A}\left(\frac{a_x}{g}\right) = 0 \end{aligned}\right\} \tag{10}$$

Equations (10) constitute two coupled, first-order differential equations for the quantities V and θ as functions of time. To complete the system of necessary equations, relations must be given for the distance r from the planet center to the vehicle and for the local gravity g. These are

$$\left.\begin{aligned} \frac{dr}{dt} &= -V\sin\theta \\ g &= g_o\left(\frac{r_o}{r}\right)^2 \end{aligned}\right\} \tag{11}$$

The three initial conditions required for solving the system of equations are the speed, path angle, and altitude at time zero. In addition to the initial conditions it is evident that the quantities C_D/C_A and C_L/C_A must be given as functions of time. Attention will now be directed toward showing how time histories of the aerodynamic coefficients for a general vehicle shape can be obtained.

The aerodynamic coefficients are, of course, not explicitly dependent on time. They are, however, generally dependent on vehicle attitude, Mach number, or speed and Reynolds number each of which is related to time. The variations of Mach number and Reynolds number with time can be determined approximately from the calculation of the trajectory so that no serious problems are foreseen in accounting for variations of aerodynamic coefficients with these parameters. A major problem does exist, however, by virtue of the fact that aerodynamic coefficients can be strongly dependent on vehicle attitude relative to the velocity vector and that excursions of attitude from a mean can be large during a passive entry. It is apparent that either attitude must be measured as a function of time or else vehicle attitude considerations must be eliminated from the problem. Consider first the possibility of deducing attitude as a function of time from the accelerometer measurements.

The vehicle attitude relative to the velocity vector can be expressed in terms of two angles; incidence angle σ and roll angle φ. (See fig. (1) for definition of these angles.) These two angles can be determined from a time history of the x, y, and z accelerations in combination with aerodynamic data for the chosen configuration experimentally measured in ground based facilities. The procedure for doing this is based on the fact that there are unique values of σ and φ for each combination of C_N/C_A and C_Y/C_A. Thus, a plot of the variation of C_N/C_A with C_Y/C_A showing lines of constant

σ and φ can be prepared from experimental data. If the x, y, z accelerometer outputs are recorded simultaneously at any instant of time, then the values of C_N/C_A and C_Y/C_A needed to enter the plot are given by a_z/a_x and a_y/a_x, respectively (ratio eqs. (1)). Once incidence and roll angles are determined, the quantities C_D/C_A and C_L/C_A can be obtained from plots of experimental data or from results of theoretical predictions. It is obvious that this procedure for obtaining time histories of the aerodynamic quantities is subject to a number of sources of error and that a relatively large amount of accelerometer data would be needed to describe the complete time history of the oscillatory angles σ and φ. It will be shown in the next section that all of the problems brought about by having to measure time histories of these oscillatory angles can be eliminated by a vehicle with spherical external shape. First, however, a general method for solving the trajectory equations will be discussed.

The method of solving the trajectory equations (eqs. (10) and (11)) is not entirely straightforward since all of the initial conditions are not known a priori. For example, the initial value of r, or, equivalently, the altitude at time zero, would not be known. Knowledge of the altitude at the final time can be used to solve iteratively for the initial altitude, however. The final altitude would, of course, be zero if the trajectory equations were integrated to the time of vehicle impact with the planet surface. Actually, the altitude at any one instant of time could be used instead of altitude at entry to obtain a unique solution to the equations.

An interesting and possibly useful method for deducing entry angle is suggested by the foregoing. Since the problem is governed by three first-order differential equations, three initial conditions are required for obtaining a unique solution. However, as discussed in connection with the initial altitude condition, not all of the information used to effect a unique solution has to apply at time zero. This suggests the possibility of using ambient pressure measured by an independent technique (e.g., a pressure gage) at low altitude and low speed as an imposed condition from which entry angle can be deduced. For example, suppose that entry speed and final altitude are known and the altitude and path angle of entry are unknown. The procedure would be to select a number of entry angles arbitrarily. Corresponding to these choices there would be unique entry altitudes satisfying the final altitude requirements. Also, unique histories of pressures as functions of time and altitude would be obtained from equations (5) and (8). The correct choice of entry angle would be that which would give an ambient pressure at a prescribed time equal to the pressure measured by the independent method. The accuracy to which entry angle can be determined by this method depends primarily on the accuracy of the pressures given by the independent techniques. Further consideration of this method is beyond the scope of the present study.

Simplified Equations for a Spherical Entry Body

All complications and attendant inaccuracies resulting from having to consider variations of aerodynamic coefficients with vehicle attitude can be eliminated entirely by a vehicle with spherical external shape. This fact can be brought into evidence by recognizing that the resultant aerodynamic force on a sphere in any attitude is just the drag. In this case, the accelerometer equations (eqs. (1)) can be combined to give

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} = \frac{C_D A}{m}\left(\frac{1}{2}\rho V^2\right)$$

The above equation can be solved for density. The result, in terms of the resultant acceleration, is

$$\rho = \left(\frac{m}{C_D A}\right)\frac{2}{V^2}\,a \tag{12}$$

Note that the aerodynamic term appearing in this equation, C_D, is independent of body attitude. This is in contrast to equation (2) for an arbitrary body shape which contains the attitude-dependent axial force coefficient.

The equations governing the trajectory of a sphere are independent of aerodynamic coefficients. They are obtained from equations (9) and (11) by setting the lift coefficient to zero and by using equation (12). The resulting equations are given below.

$$\left.\begin{aligned}
\frac{1}{g}\frac{dV}{dt} + \frac{a}{g} - \sin\theta &= 0 \\
\frac{V}{g}\frac{d\theta}{dt} + \left(\frac{V^2}{gr} - 1\right)\cos\theta &= 0 \\
g &= g_o\left(\frac{r_o}{r}\right)^2 \\
\frac{dr}{dt} &= -V\sin\theta
\end{aligned}\right\} \tag{13}$$

Aerodynamic coefficients now enter the problem only through the drag coefficient in equation (12) and C_D for a sphere is not dependent upon body attitude. If the vehicle attitude is needed for some other purpose, it can be readily obtained from the following equations:

$$
\left.
\begin{aligned}
\tan \sigma &= \sqrt{\left(\frac{a_y}{a_x}\right)^2 + \left(\frac{a_z}{a_x}\right)^2} \\
\tan \varphi &= \frac{a_y}{a_z}
\end{aligned}
\right\} \tag{14}
$$

The quadrants of the angles σ and φ can be obtained by considering the algebraic signs of the measured accelerations.

Errors in Atmosphere Definition Due to Inaccurately Measured Accelerations

The definition of a planetary atmosphere by the method under consideration is subject to errors from a number of sources. Extensive analysis is required to identify each of these sources, to estimate the magnitudes associated with them, and then to determine their individual and combined effects on the definition of an atmosphere. One of the first sources of error requiring examination is the accelerometers themselves from which the data are obtained. The results of such an examination are reported in this section. The present analysis is not intended to be exhaustive but rather to illustrate the accuracy to which an atmosphere can be defined by a spherically shaped entry body with instruments having presently obtainable levels of accuracy.

The accuracy of many kinds of accelerometers is within a given fraction of the maximum value the instrument can measure. Of course, this means that the measurement errors, in terms of percentages of local values, are smaller when the instrument is operating near the upper end of its range than near the lower end. This situation is unfavorable in the present application since the instrument must be designed to measure the highest acceleration that might be encountered and yet for the bulk of the time of many entry trajectories the accelerations experienced by a body are an order of magnitude or more lower then peak values. Thus considerable emphasis is placed on the actual magnitudes of accelerations expected during an entry and hence the accuracy of atmosphere definition will depend upon the particular planet, entry conditions, and vehicle characteristics being considered.

The planet Mars was selected for this analysis. Several models of the Mars atmosphere believed to bracket that which actually surrounds the planet are presented in reference 4. The approximate analytic forms of the maximum and minimum scale height atmospheres given in reference 4 were used in the present study. A typical probe entry speed of 26,000 ft/sec and entry angles of 50° and 90° were chosen for entry conditions. It was assumed that the spherical entry body had a constant value of m/C_DA of 0.25 slug/ft^2.

The trajectory equations (eqs. (13)) were programmed for solution on an electronic digital computer. In addition to having the initial conditions, the problem was programmed to accept a time history of resultant vehicle acceleration as input. To prepare sample acceleration histories for study an exact record was first obtained from an entry trajectory computer program for a particular model atmosphere and set of entry conditions; then the desired error factor was applied. An exact acceleration history was used to check the validity of the entire procedure. It was found that the density, pressure, and scale height of the atmosphere defined by machine solution agreed exactly with the model atmosphere used in obtaining the acceleration history originally.

The first results to be discussed are those obtained with single range instruments designed to measure any acceleration that might be encountered for the chosen conditions. For this analysis, the maximum acceleration is encountered entering the minimum scale height atmosphere with an entry angle of 90° and the minimum acceleration corresponds to entering the maximum scale height atmosphere with an entry angle of 50°. The values of the maximum and minimum possible resultant accelerations are 438 and 112 times the sea-level gravity of Mars, respectively. Choosing a range of 0 to 450 g_o for the instruments allowed a small margin in the operating ranges of the instruments. It is further assumed that the error in the resultant acceleration is constant at 0.1 percent of the maximum value measurable by any one of the instruments. To prepare the accelerometer records simulating entry into the maximum and minimum scale height atmospheres with entry angles of 50° and 90°, the error of 0.45 g_o was subtracted from the respective exact time histories. The variations of density with altitude defined by means of these acceleration histories are shown in figure 2 where they are compared to the exact atmospheres.

The results of figure 2 show that the definition of the minimum scale height atmosphere is very good over most of the altitude range regardless of the entry angle. In contrast, the definition of the maximum scale height atmosphere is very poor over the entire altitude range whether the entry angle is 50° or 90°. The situation shown in figure 2 can be improved considerably in a number of ways. Some of these will be discussed herein but first it is necessary to understand how the errors in density structure resulting from measurement errors accumulate to the extent shown in figure 2.

Errors in defining atmosphere density structure can be attributed to three sources, each a result of the errors in measured accelerations and each related by the common variable, time. First, there is the error in measured acceleration. Inspection of equation (12) shows that the error in density at any time is directly proportional to the error in resultant acceleration at that time. Second, there is an error in calculated vehicle speed at each instant of time. The density error is inversely proportional to the square of the error in speed as shown by equation (12). The speed error is cumulative with time and is a direct result of integrating an erroneous acceleration measurement. It is presumed that the speed at entry is known exactly so that the error in speed is zero at time zero and increases to a maximum at the final time. The third source of error arises from having to relate altitude to time in order to provide the link between altitude and density. This error in altitude results from integrating the time history of speed, which itself is not accurate, to obtain the total change in altitude history during entry. The time at which altitude is zero is defined by impact of the probe with the planet surface. In effect, the error in altitude is a maximum at the time of entry and it decreases to zero at the time of impact.

The manner in which the magnitudes of the errors in resultant acceleration, speed, and altitude vary with time is shown in figure 3. In this illustration, the errors obtained by flying the most favorable trajectory (minimum scale height atmosphere, $\theta_E = 90^\circ$) are compared to the errors obtained by flying the least favorable trajectory (maximum scale height atmosphere, $\theta_E = 50^\circ$). It is immediately evident from these results that the large difference in flight time between the two trajectories is a major factor to consider. The time to complete the entry into the maximum scale height atmosphere with the smaller path angle is greater by more than an order of magnitude than the time to complete the entry into the minimum scale height atmosphere with the larger path angle. The resultant acceleration is small during most of the time of the longer trajectory so that the assumed 0.45 g_o error in its measured value is a large fraction of the total. The effects on speed and altitude determination due to integrating this large error over a long period of time are clearly evident in figure 3.

Two methods which can be used to improve the accuracy in defining atmosphere are immediately evident. Either the period of time over which large errors in acceleration measurements must be integrated can be shortened or the accuracy of the acceleration measurements can be improved. The levels of improvement that can be expected from each of these methods will be illustrated using the least favorable trajectory as an example.

Consider first the situation in which the time period of the problem is reduced. In this case it is assumed that altitude can be deduced by some other means after the speed of the probe is reduced by aerodynamic drag to relatively low values. For purposes of demonstration it will be assumed that the altitude is known at the respective times when the speed is 500, 750, and 1000 ft/sec. The values of time corresponding to these speeds are 116.8, 80.0, and 67.2 seconds, respectively. These can be compared to the time for the complete trajectory from entry to impact of 369.6 seconds. The variations of atmosphere density with altitude computed for these conditions are shown in figure 4. It is evident that this is a powerful method for improving atmosphere definition over that obtainable by relying solely upon accelerometer information throughout the entire trajectory. It is recalled that in the results of figure 4 the altitude was assumed known exactly at each of the chosen speeds. The effect of inaccuracies in the knowledge of these altitudes was investigated. It was found that the effect was essentially to cause the curves in figure 4 to translate in altitude by the amount of the assumed uncertainty. A possible method for obtaining the altitude at the time when the speed is a certain low value consists in measuring the speed with a conventional speed indicator during the subsonic portion of the flight prior to impact and then integrating to get altitude change. Of course, other techniques such as directly measuring ambient pressure and temperature could be used to define the atmosphere structure at altitudes below those where the accelerometer method is used. Further investigation of these methods has not be made.

Consider now the possibility of improving atmosphere definition by increasing the accuracy of the measured accelerations. The results of figure 3 showed that the errors in measured accelerations could be large over a considerable portion of the trajectory if the instruments were designed to measure over the complete range of expected values. Since the vehicle experiences low values of acceleration most of the time in a long trajectory, it is reasonable to consider using two different sets of instruments; one designed to measure over the entire range of expected values and one designed to measure over a more limited range. If the accuracy of each of the sets of instruments is given as a specified percentage of the respective maximum values measurable, the net result is increased accuracy over the single range system in terms of percentage of local values. It can be reasoned on the basis of the results of figure 3 that for each time history of acceleration there exists an optimum range over which the low range system should be designed to operate. The flight speed, as determined from integrated acceleration data, can never be known more accurately than it is known at the beginning of the integration. Thus, if the low range system is designed to operate over a range of very small accelerations, then the error in speed is already quite large before the potential benefits of the dual range system can be realized. On the other hand, if the low range system is designed to operate over too large a range of accelerations, then the speed error would be small at the time of switching from the high range system to the low range system but the errors in measured accelerations would be larger over a longer period of time. The predicted variations of atmosphere density with altitude obtainable with dual accelerometer systems with several different ranges for the low range system are compared in figure 5 to that previously shown for the single range system. In each case the values measured by the instruments are assumed to be accurate to a constant 0.1 percent of the maximum value measurable by the instrument.

The results of figure 5 show that the dual system provides a much better definition of the density structure than does the single range system. Furthermore, the results show that the optimum range for the low range accelerometers is somewhere between 0-4.5 g_o and 0-112 g_o for this example. The range of 0-112 g_o was chosen because the maximum accleration experienced during entry into the maximum scale height atmosphere with an entry angle of 50^o is 112 g_o. Although the dual system is certainly better than the single system, comparisons of the results of figure 5 with those of figure 4 show that changing from the single range system to the dual system is not so effective as using a single range system in conjunction with some other method for defining the atmosphere density structure after the speed is reduced to subsonic values.

The ambient pressure in the atmosphere depends on the integrated product of local gravity, density, speed, and sine of the path angle over the trajectory (eq. (5)). The computed variations of pressure with altitude for both the minimum and maximum scale height atmospheres are compared to exact results in figure 6. The calculations were made using the previously discussed single range accelerometer system for the portions of the trajectory where the exact speed was greater than 750 ft/sec. The results for the minimum scale height atmosphere obtained from data for a steep 90^o entry show the best that can be expected from this method, while the results for the maximum scale height atmosphere obtained from data for a 50° entry are indicative of the poorest definition of pressure structure using this system. In both cases the atmosphere pressure is defined reasonably well over large ranges of altitude.

CONCLUDING REMARKS

A detailed procedure has been devised for obtaining density and pressure structure of a planetary atmosphere from measurements of accelerations experienced by a vehicle making an uncontrolled entry into the atmosphere. It has been shown that the need for a complex method of determining the time history of vehicle attitude from acceleration data and the attendant source of potentially large errors can be eliminated completely if the accelerometers are carried aboard a spherically shaped vehicle.

Results of an error analysis, in which estimates were made of the accuracy to which extreme model atmospheres for Mars could be defined, showed that either the accelerations must be measured very accurately or the time period over which large measurement errors are integrated must be kept short. It is suggested that the latter can be accomplished by the method involving acceleration measurements for the high-speed part of the trajectory only. Further effort is needed to examine various methods which could be used to define atmosphere structure over the portion of the trajectory where flight speed and hence accelerations are relatively low.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Nov. 23, 1964

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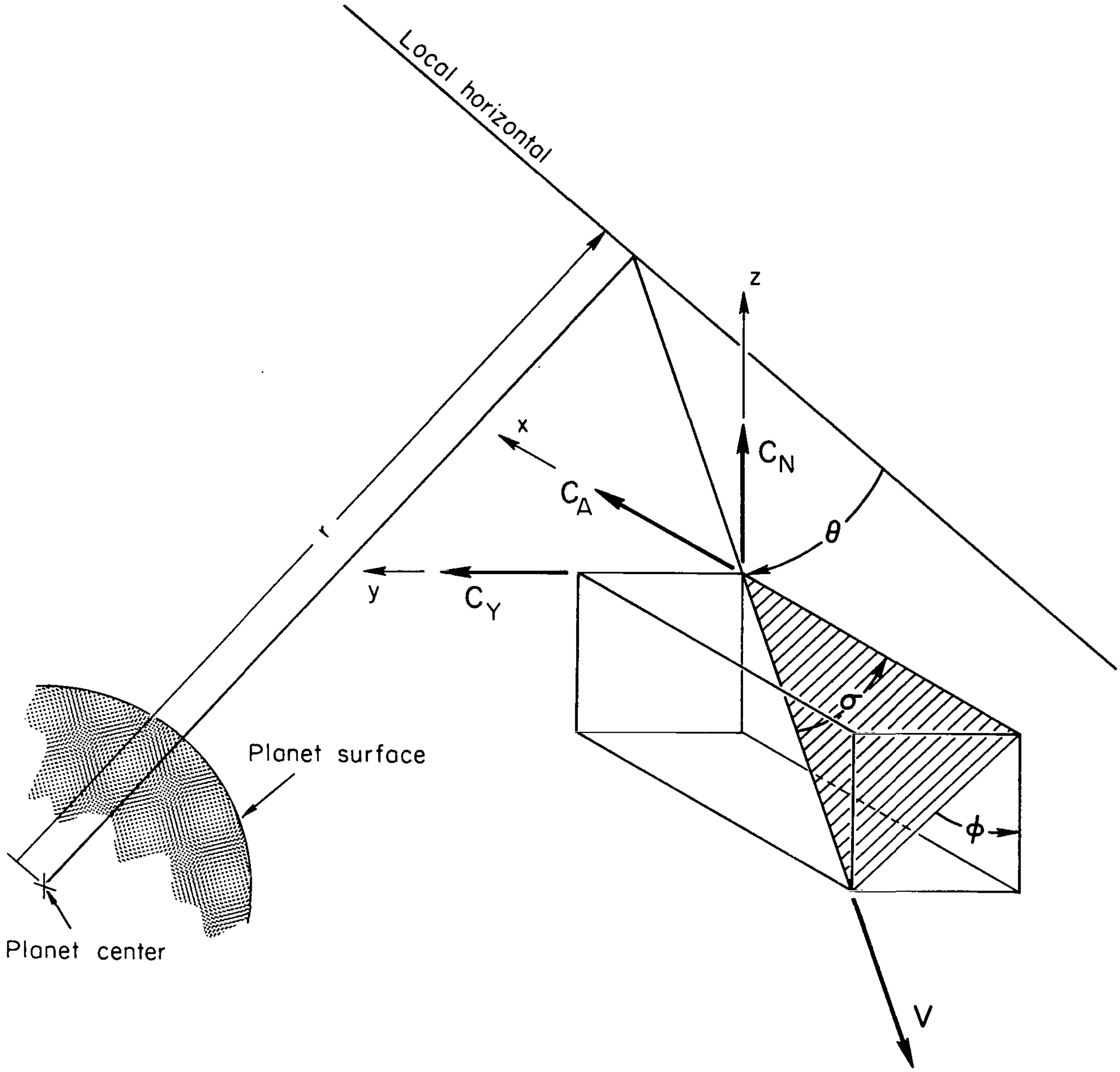

Figure 1.- Coordinate system.

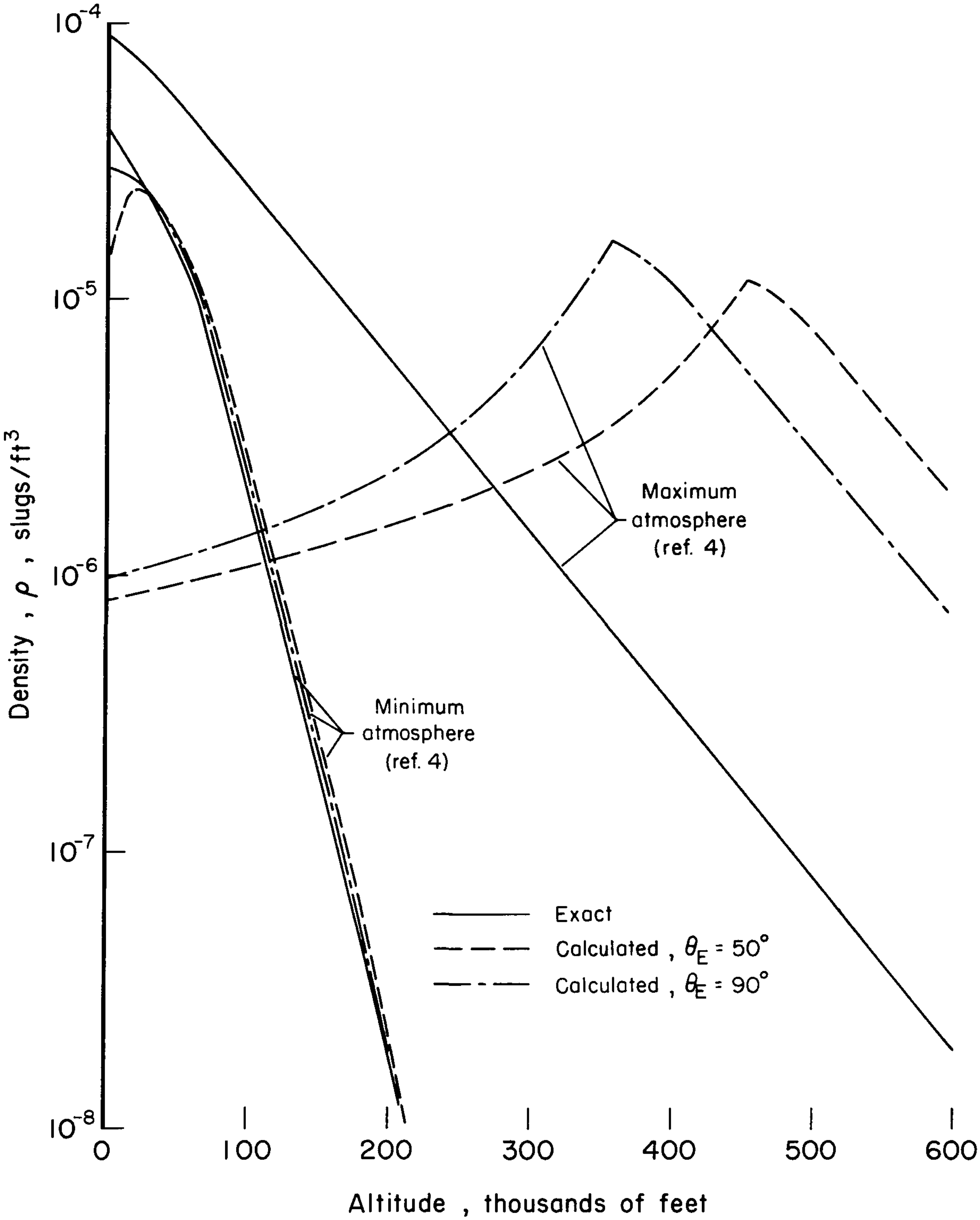

Figure 2.- Extreme model atmospheres for Mars calculated from accelerometer data simulating that obtainable from a single range system accurate to 0.1 percent of the maximum value measurable; acceleration error = 0.45 g_o; m/C_DA = 0.25 slug/ft^2; V_E = 26,000 ft/sec.

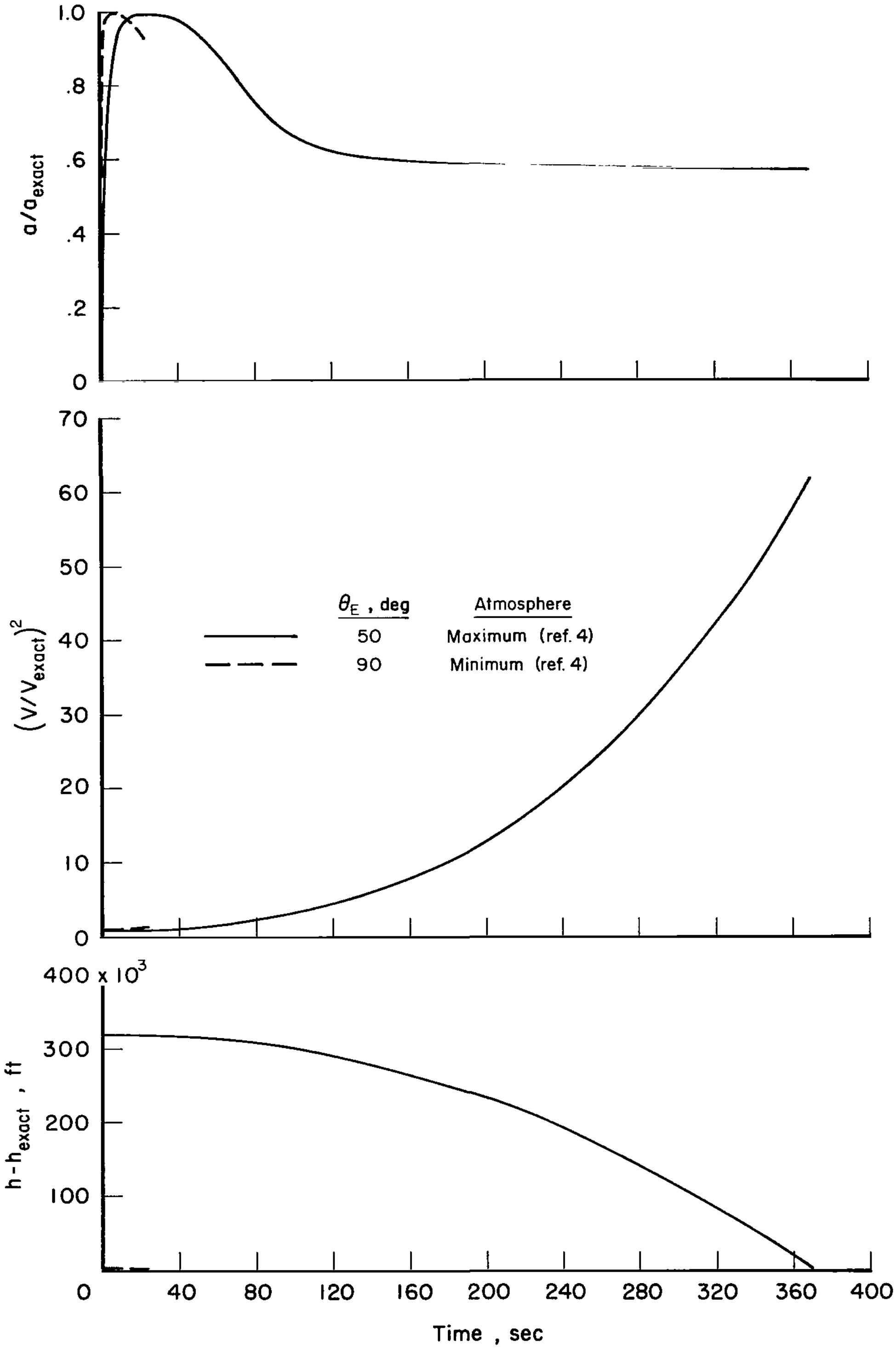

Figure 3.- Effects of a 0.45 g_o error in measured acceleration on the calculated time histories of speed and altitude; m/C_DA = 0.25 slug/ft^2; V_E = 26,000 ft/sec.

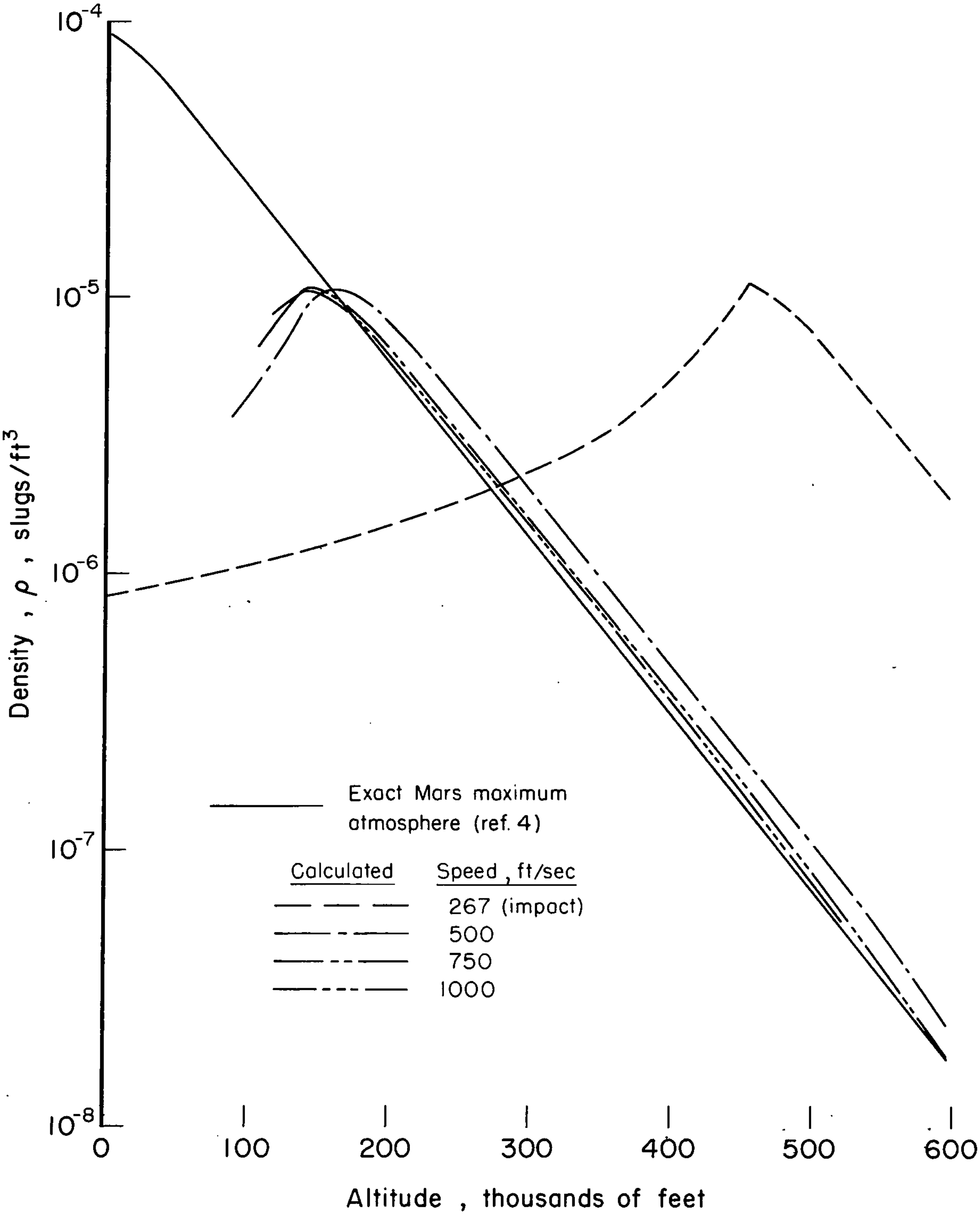

Figure 4.- Effect of knowing the exact altitude at various values of speed on the definition of density variation with altitude. Single range accelerometer system accurate to 0.1 percent of maximum measurable value; acceleration error = 0.45 g_o; m/C_DA = 0.25 slug/ft^2; V_E = 26,000 ft/sec; θ_E = 50°.

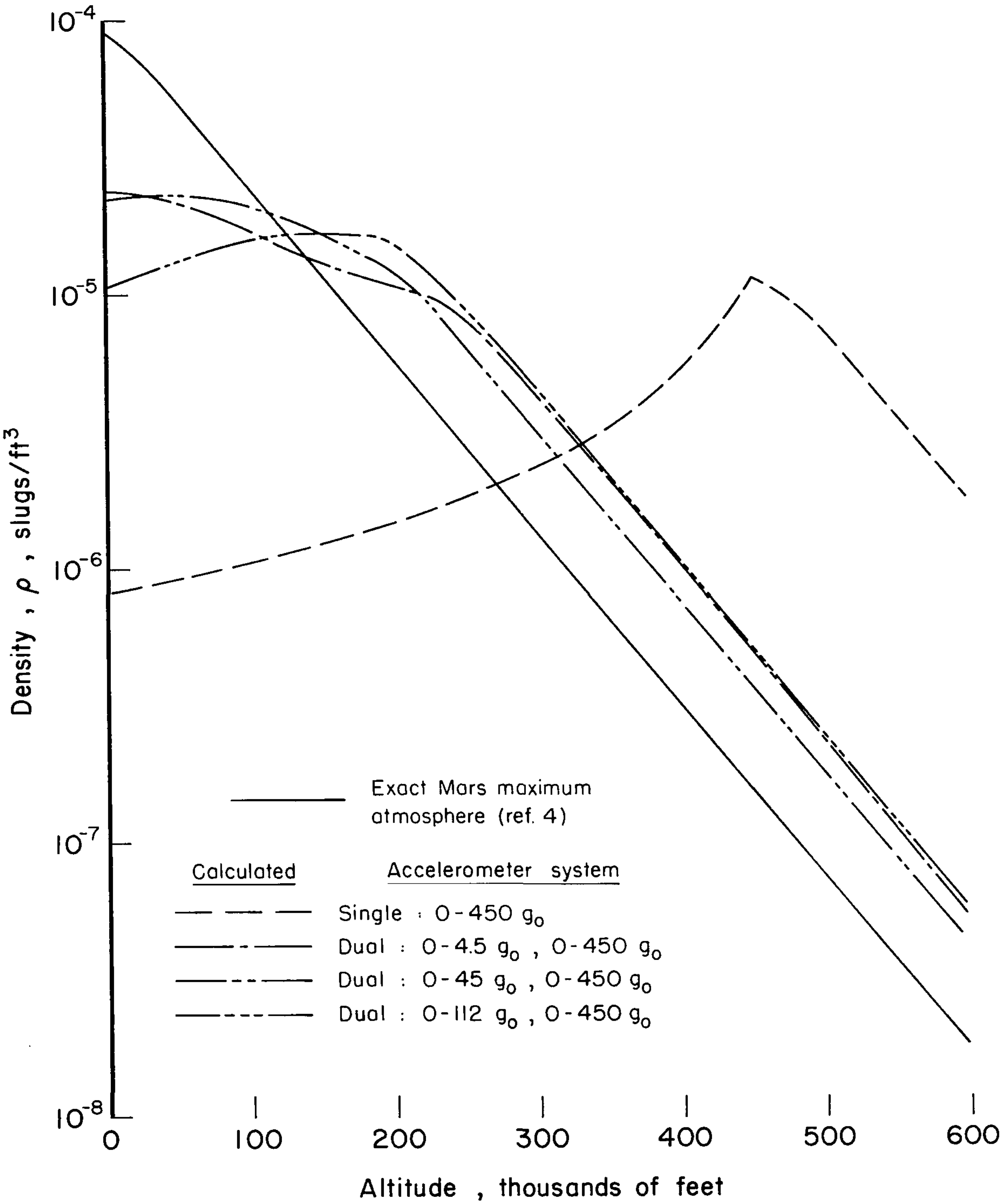

Figure 5.- Effect of inaccuracy in measured accelerations on atmosphere definition. Measurements accurate to 0.1 percent of maximum measurable value; $m/C_DA = 0.25$ slug/ft^2; $V_E = 26{,}000$ ft/sec; $\theta_E = 50^\circ$.

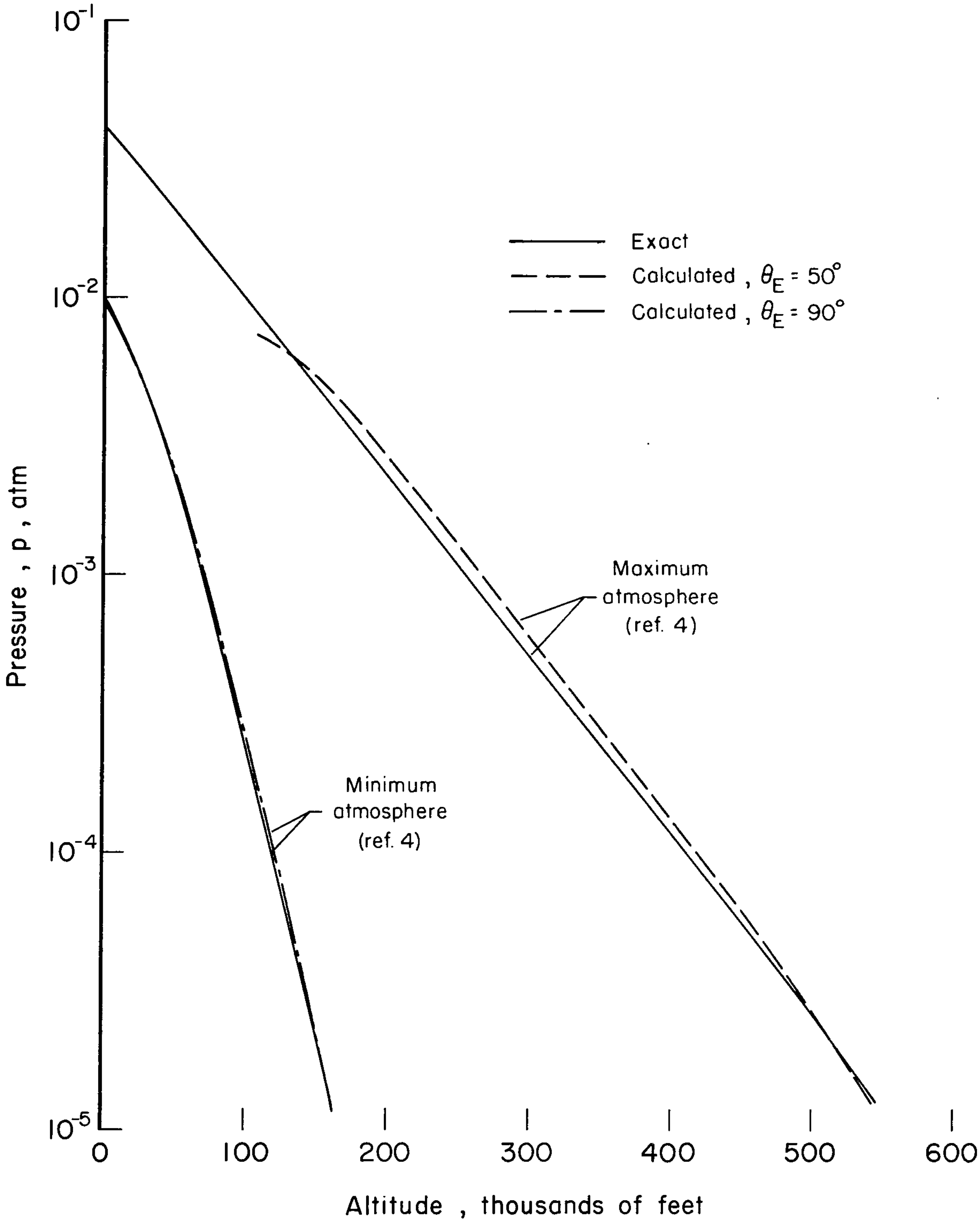

Figure 6.- Pressure structure of Mars atmospheres calculated from accelerometer data. Data obtained for altitudes above those corresponding to flight speeds of 750 ft/sec or greater. Single range accelerometer system accurate to 0.1 percent of maximum measurable value; acceleration error = $0.45 g_o$; $m/C_D A$ = 0.25 slug/ft^2; V_E = 26,000 ft/sec.

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